Vanadium moments and magnetization depth profile in Fe/V superlattices

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With an appropriate choice of elements and structures, metallic multilayers feature oscillating magnetic coupling between ferromagnetic layers and giant magnetoresistance effects. Fe/V superlattices present a whole variety of magnetic behaviors, depending on the thickness (t_{Fe}, t_V) and on the crystal orientation. Until recently, the magnetic properties of V in these layers were subject to controversy. Vanadium is known to acquire a magnetic moment when in contact with Fe, e.g. when diluted in an Fe matrix or deposited on an Fe crystal. In superlattices and multilayers it is difficult to detect and quantify the magnetic moment of vanadium which is small, in the presence of large amounts of Fe, and element selective techniques based on electron analysis are unable to probe buried interfaces. In the past [1], we used x-ray resonant magnetic scattering (XRMS) to investigate V magnetism in Fe/V superlattices of the type (5 ML Fe / n ML V)$_m$ grown on MgO(001). Three samples were considered, with (n=1,m=80, 2d=16.5 Å), (n=2, m=60, 2d=22.2 Å) and (n=5, m=40, 2d=30.6 Å).

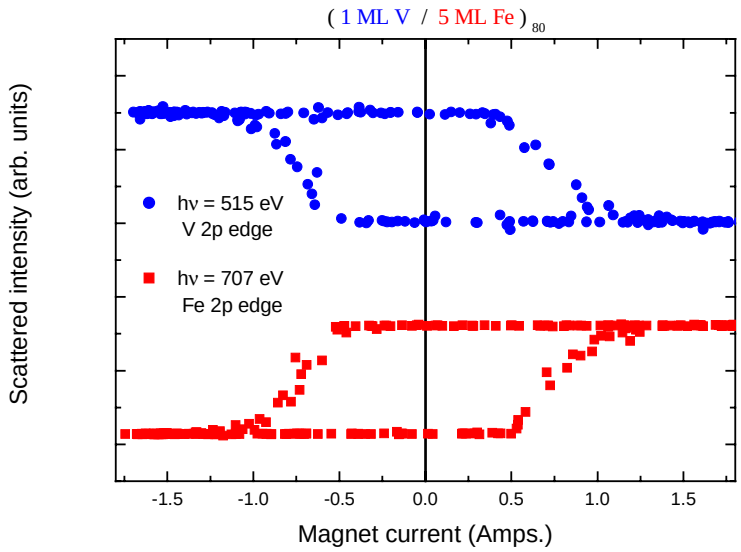

Figure 1. Element specific hysteresis loops obtained by measuring the field dependent resonantly scattered intensity

X-ray scattering and absorption measurements were performed on the soft x-ray metrology beamline 6.3.2 at ALS (Berkeley), using out-of-plane elliptically polarized radiation. The samples, mounted in a θ/2θ reflectometer, were magnetized along an easy axis, parallel to the surface and in the scattering plane. Absorption spectra were recorded by measuring the drain current from the sample. We measured energy dependent resonant scattering at both the Fe and V 2p edges for different scattering angles θ up to 30 degrees. θ/2θ angular scans were also performed for photon energies across the 2p resonances, including resonant Bragg diffraction spectra. With respect to previous experiments [1], we included in the experimental set up the use of an electromagnet that made possible to measure the scattered intensity as a function of the

external field. As in the visible range, we can use the magnetization dependence of the optical constants to draw a hysteresis loop with, in addition, the element selectivity that comes from tuning the photon energy to a specific core resonance. An example is shown in Fig. 1, where we compare hysteresis loops obtained by measuring the scattered intensity at the Fe and V 2p edges.

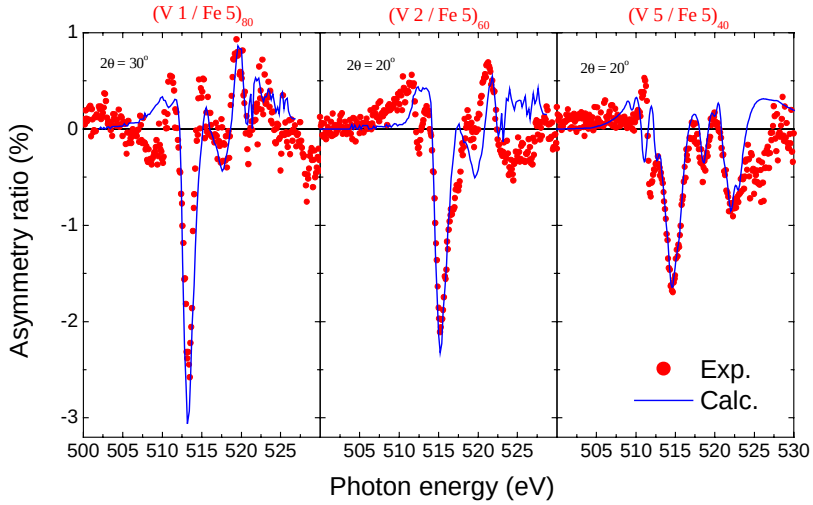

Figure 2. Experimental and calculated magnetic signal on the scattered intensity across the V 2p edge. Calculations were optimized by refining the off diagonal elements of the V dielectric tensor.

Before addressing the issue of magnetization depth profile, we briefly recall the results that we obtained in the past on these Fe/V samples [1]. Experimental scattering data were analyzed by optimizing the off-diagonal terms of the dielectric tensor on the experimental asymmetry ratio curves. This procedure permits to apply sum rules to the polarization dependent scattering in order to obtain a quantitative estimate of the element specific magnetic moments, just as in absorption spectroscopy. For each sample, the fit on the ensemble of the reflectivity curves at the Fe 2p resonances, including Bragg diffraction spectra, gave values of the magnetic moment per Fe atom between 2.1 and 2.3 μ_B, i.e. within the accuracy of the method there is no measurable change in the Fe average magnetic moment as a function of V thickness, nor with respect to bulk Fe. This also implies the ferromagnetic alignment of all the Fe layers in the stack.
By analyzing the data at the V 2p edges, we were able to determine the magnetic moment carried by the V 3d electrons (see Fig. 2). For the 1 ML V sample, we obtained a total moment of -0.66 μ_B (AF coupling between Fe and V). This value is reduced to 60 % and then to 40 % when n goes from 1 to 2 and then to 5, so that we finally obtain
n = 1 : $\mu_V = -0.66 \pm 0.20\ \mu_B$
n = 2 : $\mu_V = -0.40 \pm 0.12\ \mu_B$
n = 5 : $\mu_V = -0.26 \pm 0.08\ \mu_B$
These values represent an average per vanadium atom. It is now interesting to consider how the magnetic moment is distributed within, say, the five atomic planes forming each vanadium layer in the 5 ML Fe / 5 ML V sample. The four diagrams (a-d) in Fig. 3 represent possible magnetization profiles giving, over 5 layers, an average value of 0.26 μ_B. Resonant scattering is an ideal technique for studying magnetization depth profiles, as it is sensitive to changes in the optical constants along the sample normal, and magnetic properties affect these optical constants [2]. Reflectivity curves for the 5 ML Fe / 5 ML V sample calculated over the 5-15 degrees range assuming the four magnetic profiles of Fig. 3 were not significantly different. On the contrary,

curves in Fig. 3, calculated under resonant Bragg scattering conditions, show a variation of a factor 2 in the asymmetry ratio according to the specific magnetization profile.

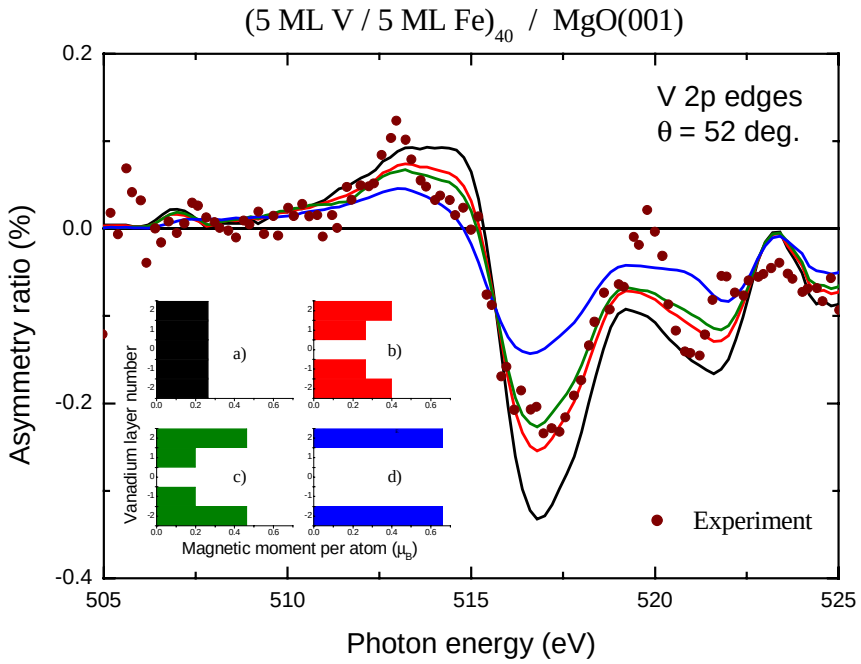

Figure 3. Calculated and experimental magnetic asymmetry ratio in the V-2p resonant Bragg scattering from a (5 ML V / 5 ML $Fe)_{40}$ superlattice. The four curves a) to d) refer to different magnetization profiles within each V sheet of five atomic layers (see bar diagrams). The same average magnetic moment per V atom (-0.26 μ_B) is assumed.

Admittedly, available experimental data do not permit to draw detailed conclusions about the magnetization profile. It is not possible, for instance, to discriminate between models b) and c) in Fig. 3. Nonetheless, we are able to prove that the magnetization of vanadium in this superlattice is neither homogeneous (model a, black curve) nor concentrated at the Fe/V interface (model d, blue curve). Our analysis indicates that, as also shown by Sève et al. in the hard x-rays regime [2], magnetization depth profiling looks like a promising direction for future developments in soft x-ray scattering experiments applied to the study of artificially structured magnetic devices.

ACKNOWLEDGMENTS
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REFERENCES

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